A Concept for Ultra High Energy Electron and Positron Test Beams at Fermilab

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CERN $e^{\pm}$ Test Beams and 2 Year Shutdown Impact

Experimenters looking for energies higher than 30 GeV will have no current comparable alternatives when CERN test beams are shutdown for 2 years at the end of 2018.

- Alternate Lab Electron and Positron Test Beam Limits
  - DESY
    - Under 10 GeV/c
  - SLAC
    - Limited to 25 GeV/c
  - Fermilab
    - Ranged from 1 - 32 GeV (highest momenta of ~31.9986 GeV/c)
    - Mixed Species
- A unique opportunity to attract a new group of users has presented itself. As CERN $e^{\pm}$ test beams are mixed species, providing higher purity, ultra high energy beams has been requested [1][2][3].

Assumed Primary Mechanism for Obtaining Ultra High Energy $e^{\pm}$

A rare decay mode for charged pions is believed to be the most effective mechanism [4].

- Branch ratio : 0.000123
  - Charged pions are to be produced as secondaries from 120 GeV/c proton beam on target.

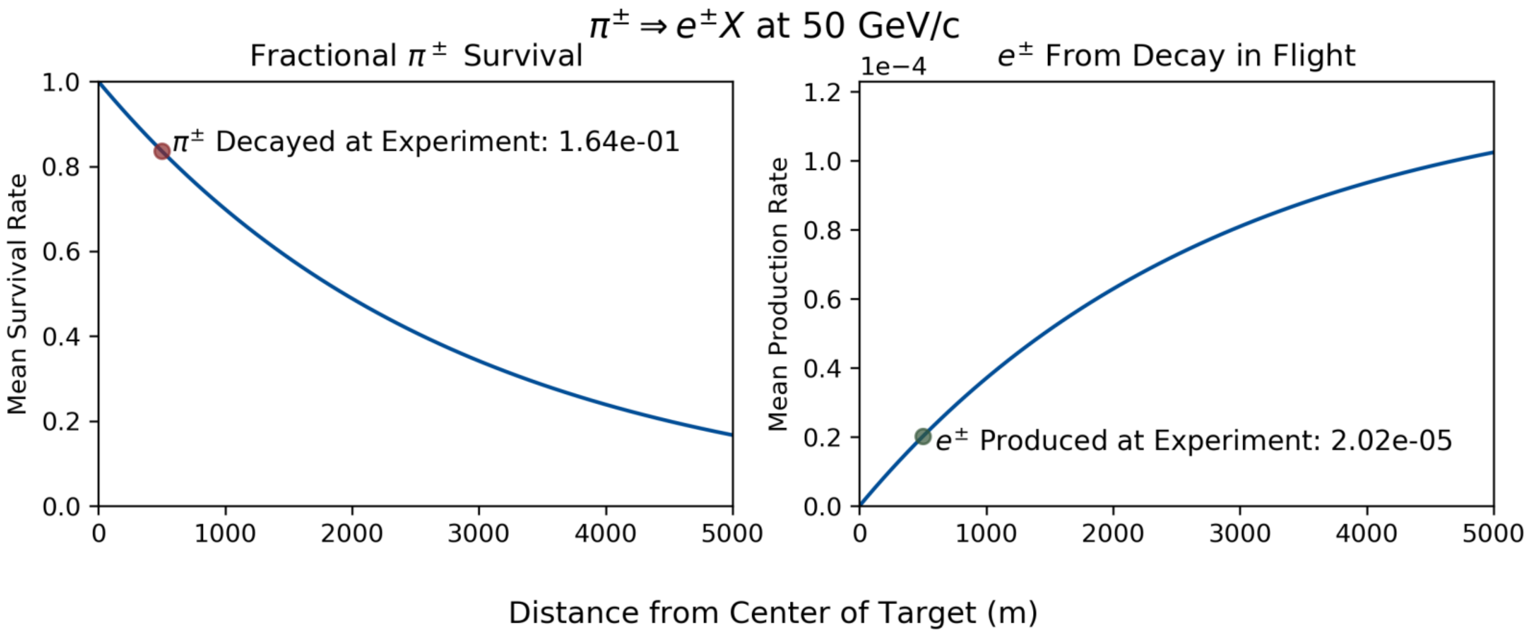
$$\pi^- \longrightarrow e^- \bar{\nu}_e$$

$$\pi^+ \longrightarrow e^+ \nu_e$$

Fractional Yield from Charged Pion Decay and e ± at Test Site

MTest distance from M01 Target Station: 460 m. 500 m used for calculation to account for additional path length from separation optics.

- Average of 50 GeV/c momentum bite, mean lifetime, and mass for $\pi^{\pm}$ used



Minimum Production Needed for Requested Spill

M01 target station is referenced which receives 2e11 proton beam

- Requested minimum spill of 5e3 $e^{\pm}$ at experiment

Prompt $\pi^{\pm}$: Minimum Production for 5E04 $e^{\pm}$ at Experiment for 50 GeV/c ± 5% p Bite					
Momentum (GeV/c)	Relativistic Factor γ	Velocity (fraction of c)	Flight Time to 500 m (s)	Pion Decay (fraction of 1)	Minimum Production Needed with 2e11 POT ($\pi^{\pm}$/proton)
47.5	340.3320469	0.999995683	1.667827676E-06	0.171588516	1.1845E-02
50	358.2441091	0.999996104	1.667826974E-06	0.163754478	1.2412E-02
52.5	376.1561784	0.999996466	1.667826370E-06	0.156602722	1.2979E-02

Prompt $\pi^{\pm}$: Minimum Production For 5E04 $e^{\pm}$ at Experiment for 40, 50, 60, 70, and 80 GeV/c					
Momentum (GeV/c)	Relativistic Factor γ	Velocity (fraction of c)	Flight Time to 500 m (s)	Pion Decay (fraction of 1)	Minimum Production Needed with 2e11 POT ($\pi^{\pm}$/proton)
40	286.5959154	0.999993913	1.667830629E-06	0.200318118	1.0146E-02
50	358.2441091	0.999996104	1.667826974E-06	0.163754478	1.2412E-02
60	429.8924192	0.999997294	1.667824988E-06	0.138454594	1.4680E-02
70	501.5407958	0.999998012	1.667823791E-06	0.119915958	1.6950E-02
80	573.1892138	0.999998478	1.667823014E-06	0.10575066	1.9220E-02

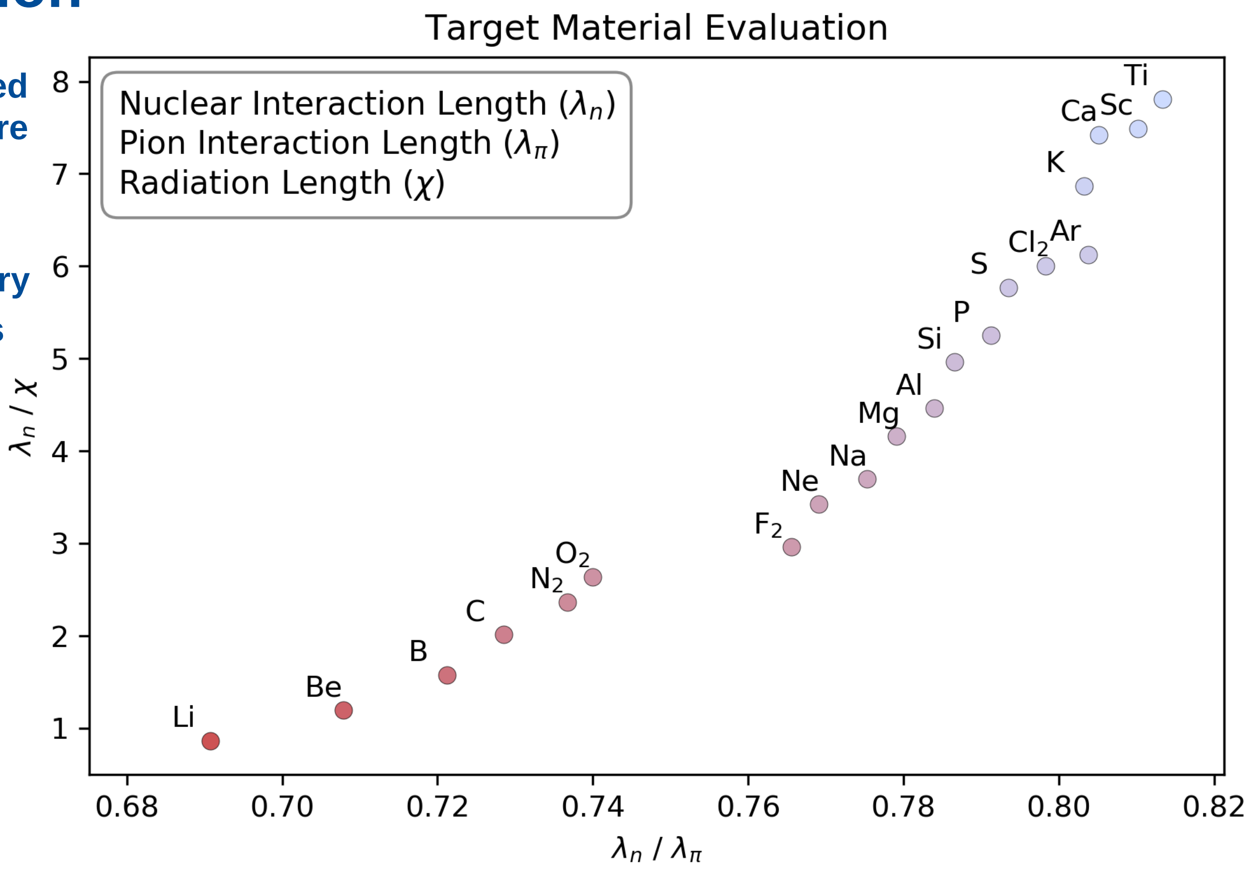
Target Material Selection Parameters

- Minimizing Nuclear Interaction Length (λ_n)
  - Describes Interaction of heavy particles with nuclei
    - Charged pions are produced from nuclear interactions
- Maximizing Pion Interaction Length (λ_π)
  - Describes Interaction of Pions within a material
    - Longer length should allow for more to escape.
- Maximizing Radiation Length (χ)
  - Describes the effect of multiple small angle deflections from Coulomb interaction
    - Longer lengths result in less scattering [5].

Material Optimization

Production potential for charged pions and minimal emittance are what's essentially compared.

Beryllium was selected as it very low on both scales and there is currently a sample in-house.



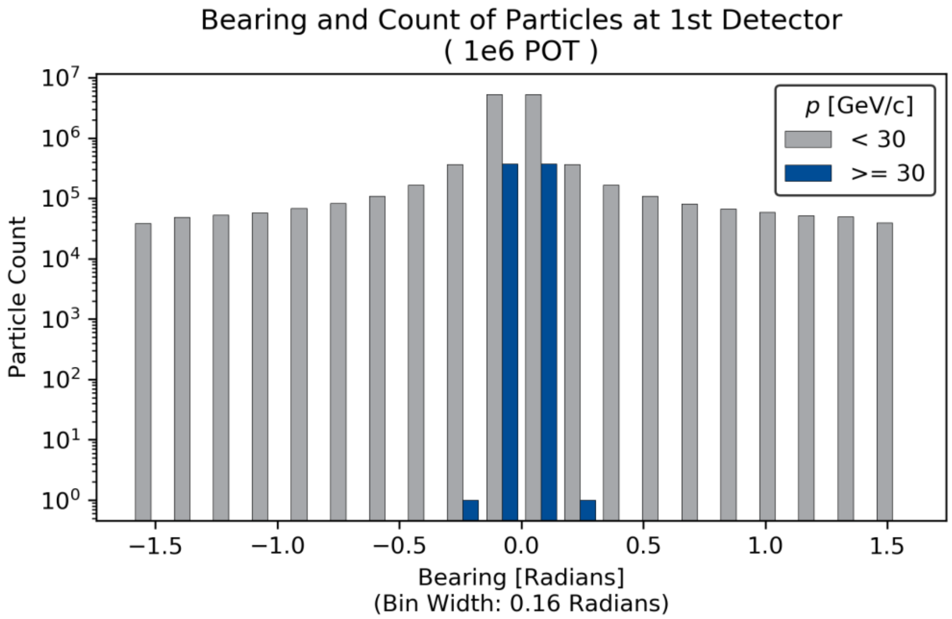
Primary Tools of Investigation

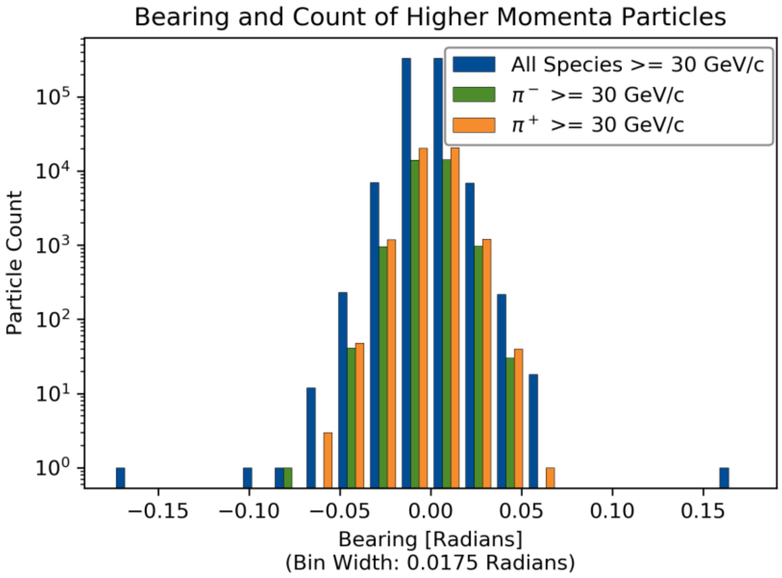
G4Beamline and the Monte Carlo Method

- G4Beamline
  - Simulates the passage and interactions of particles with matter
    - Based on GEANT4, it is optimized for beamline design [7]
    - Output of GEANT4 is a Monte Carlo text file containing kinematical variables for each particle received at a user defined virtual detector
    - Processes come from comprehensive GEANT4 physics lists [8]
- Monte Carlo Method
  - A statistical method that governs probabilities for secondary particle production
    - Uses randomly generated inputs for physics processes to cover the spectrum of outcomes [9]
    - Results produced are expressed as the mean of the normal (Gaussian) distribution
    - 1 unit of standard deviation (σ) for the distribution of the returned value N may be obtained by taking the root of N

Python 3.6.4 with Numpy, SciPy, and Matplotlib libraries were used for parsing and analysis.

Secondary Particle Production and Preliminary Design



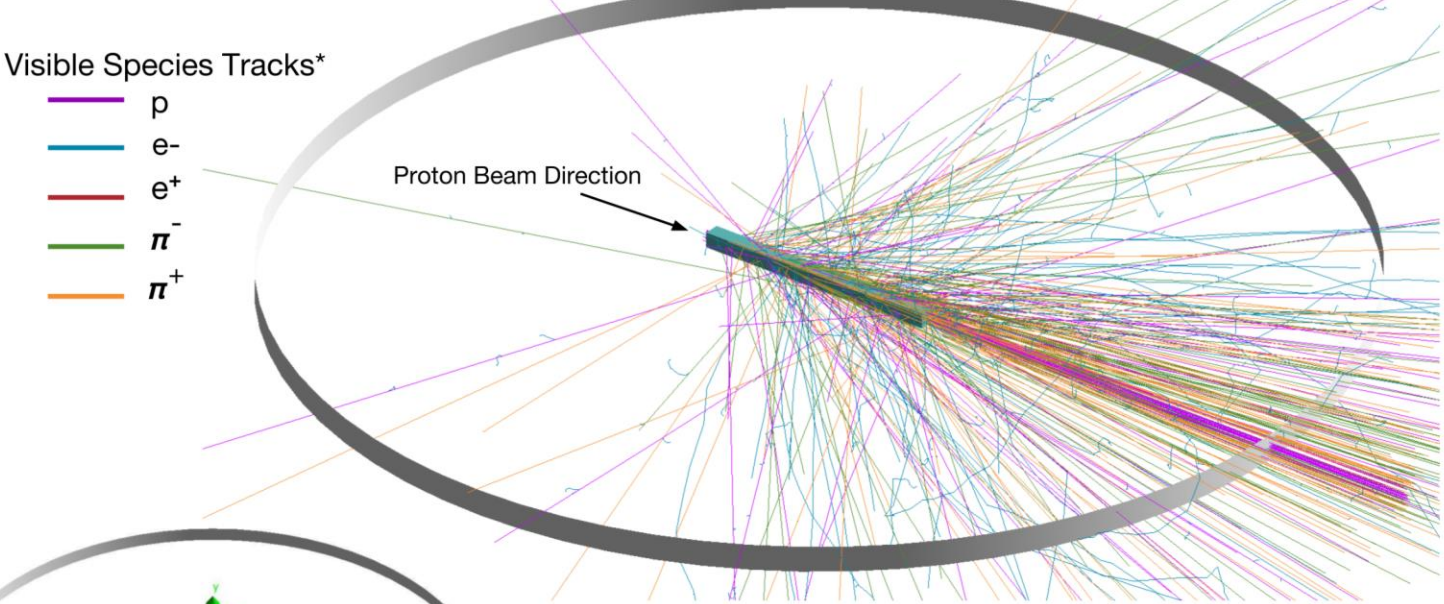


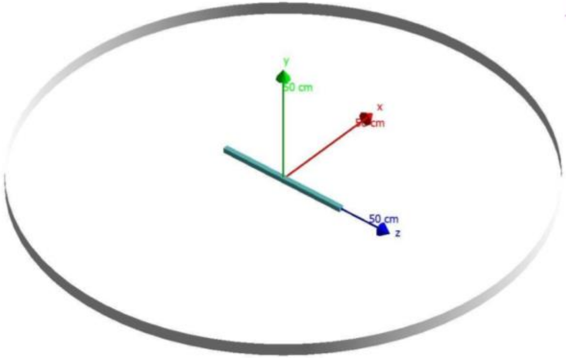
Initial simulations to understand the angular and energy spread of secondaries was done using 120 GeV/c proton beam at 1e4 events and a Be target. Results shown are from higher statistics obtained from 1e6 protons on target (POT).

Preparing for Optics

- As large solid angles cannot be transported, collimation would be needed.
  - 2 inch vertical aperture 1 m from the center of target planned
  - Virtual detector was modified to perform this pitch cut.
    - Initially a large disk immediately in front of target, detector redesigned as a cylinder 1 m in radius and 2 inches long.

G4Beamline Visualization Mode

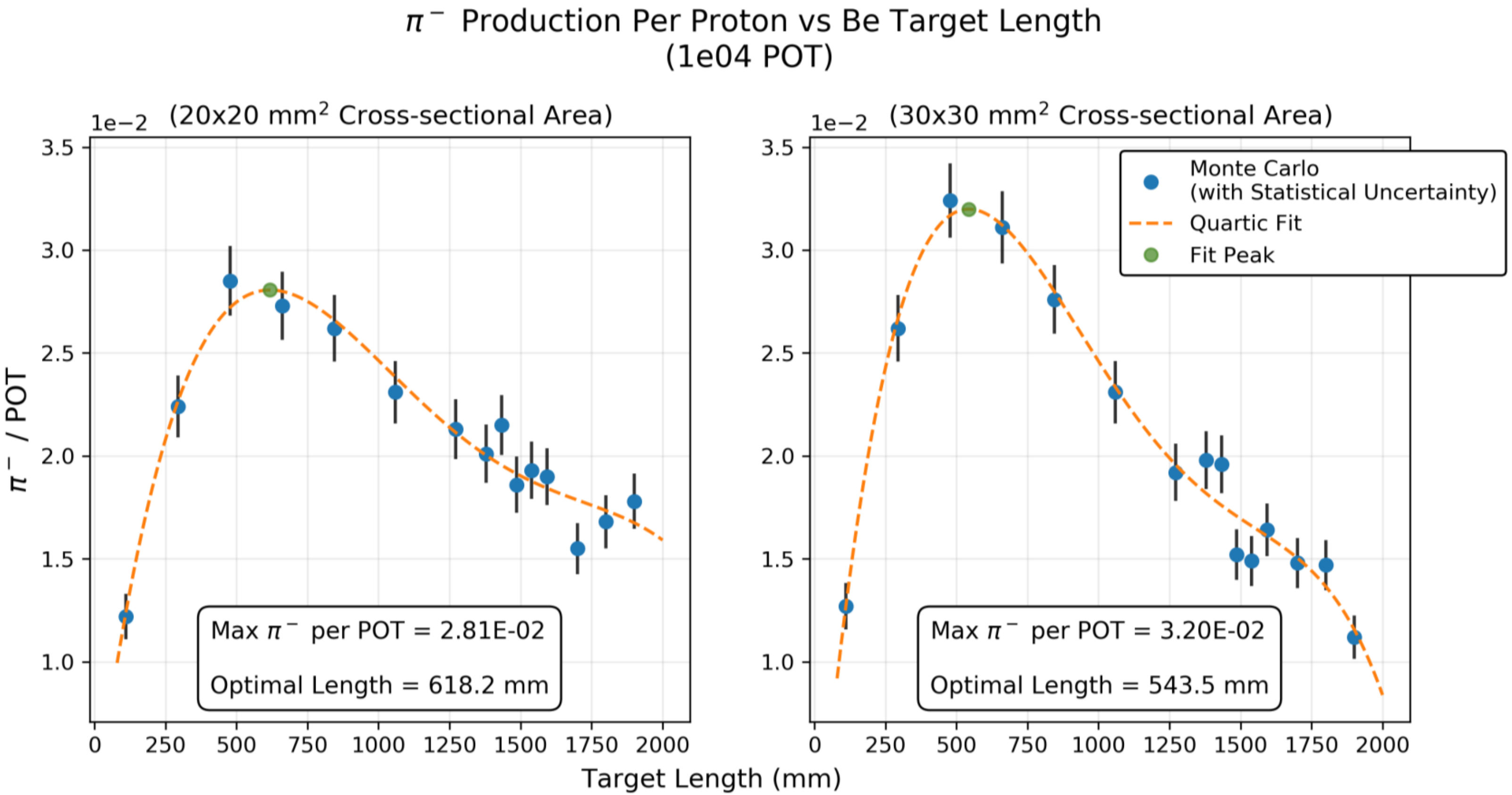




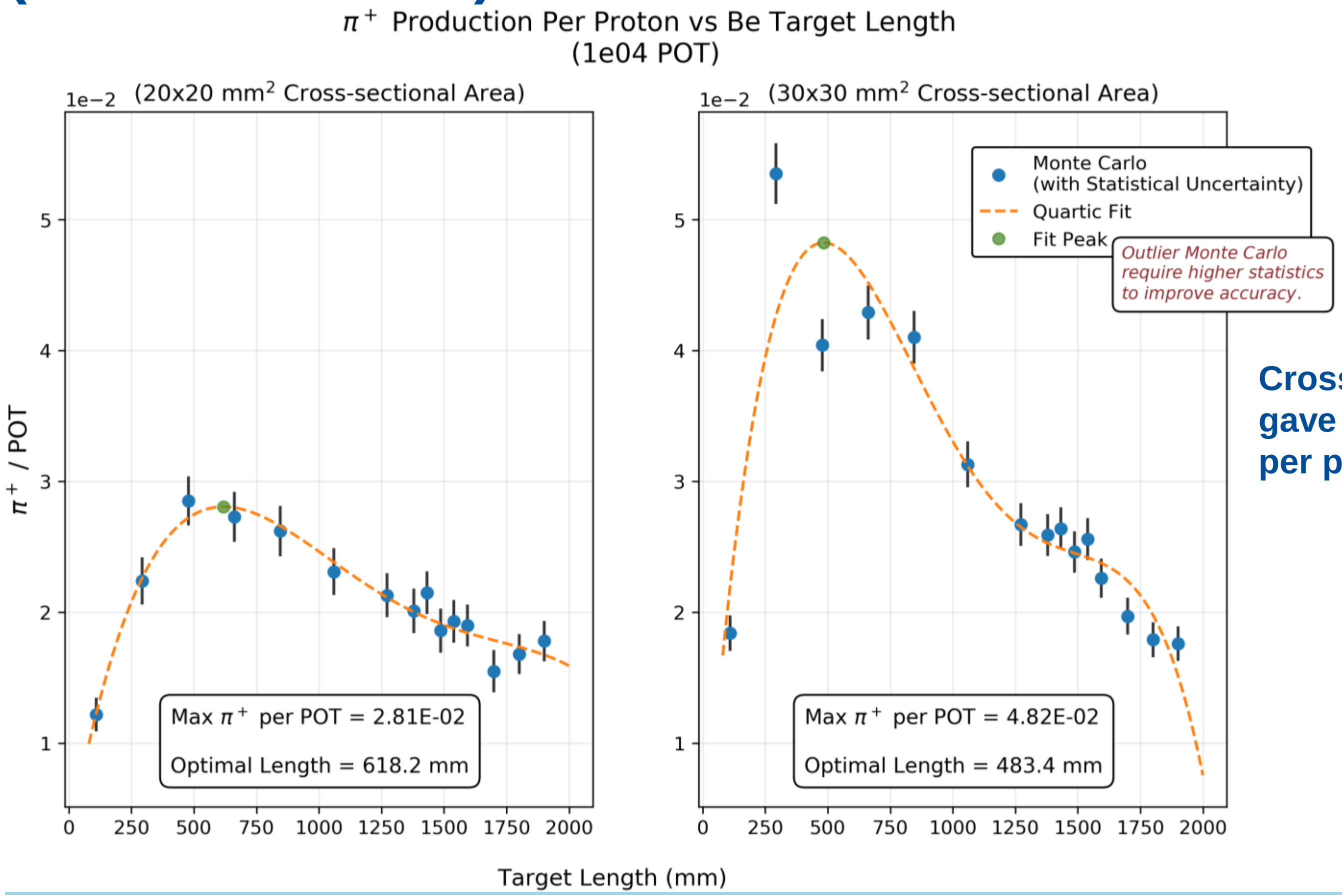
Tracks from secondary species and surviving primaries shown. Proton beam intensity set for 30 events at 120 GeV/c is incident upon a 54.35 cm Beryllium target. Transverse standard deviation of proton beam is 5 mm in x and y.

**Tracks of non-listed species disabled for clarity*

Dimensional Optimization for Charged Pion Production

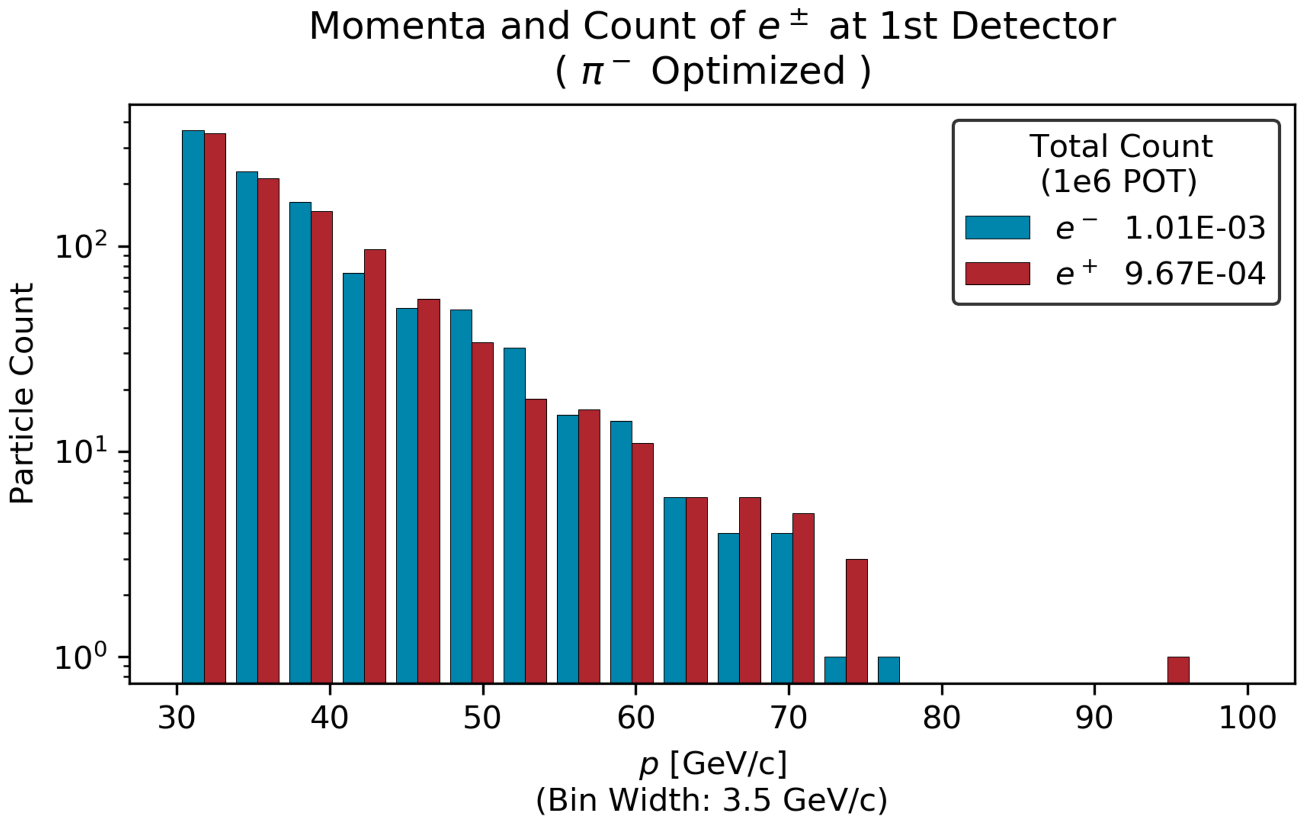


(continued for π^+)



Cross-sectional area of 30x30 mm^2 gave significantly greater production per proton on target.

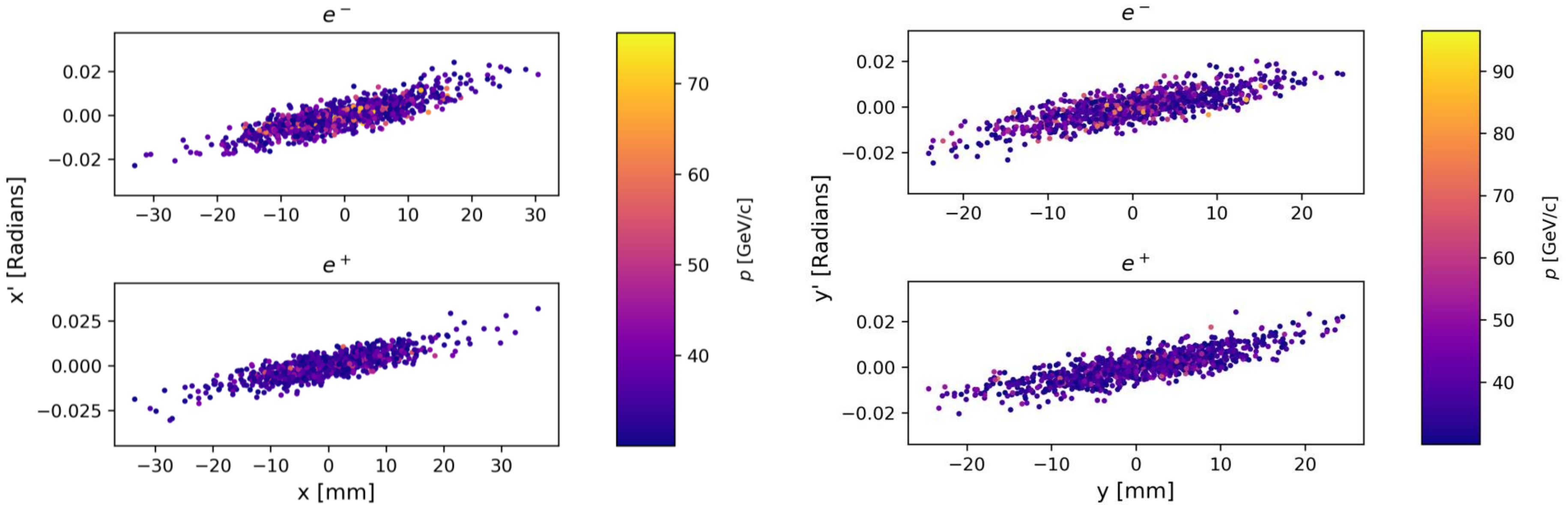
Unexpected High Energy Prompt Electrons and Positrons



- Detector inspection after running 1e6 protons on π^- optimized target revealed significant prompt $e^{\pm}$ production.

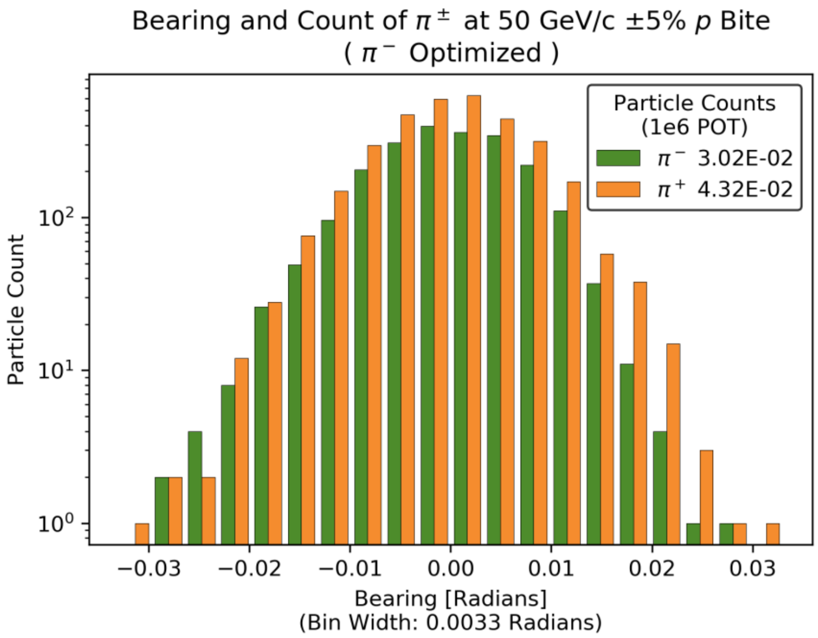
Prompt Electron and Positron Analysis

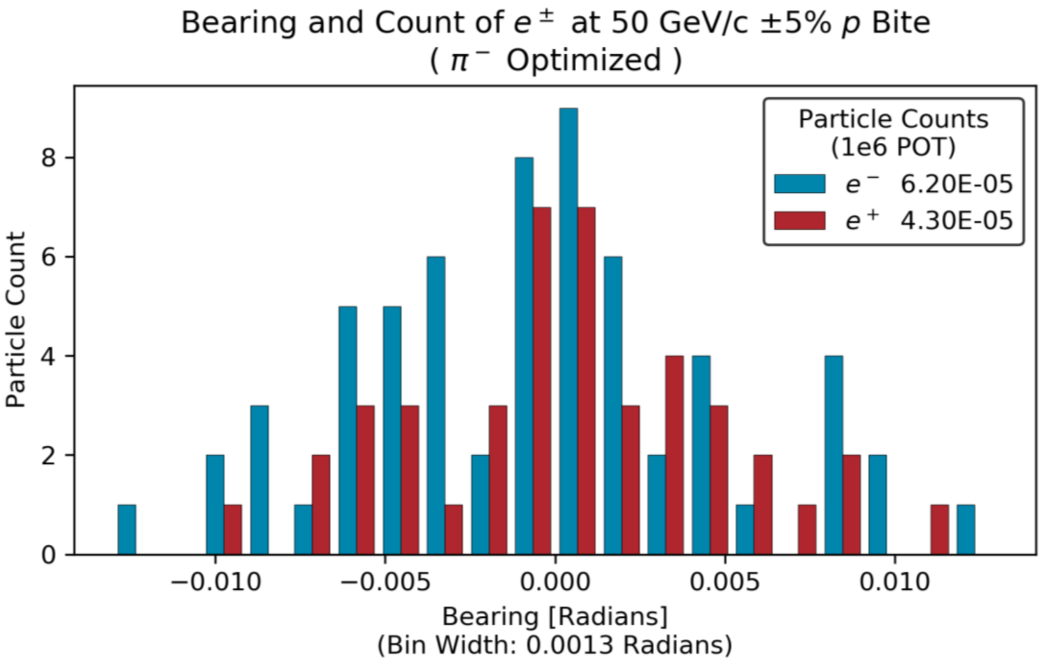
Transverse Phase Space and Momenta Distribution



Phase Space **is a conceptual method of seeing how the system changes by plotting the amplitude of particle oscillations against their derivatives (or *positions* as defined earlier). This is essential in characterizing the periodic motion of the beam.**

Higher Momentum Bites Present at Smaller Angles

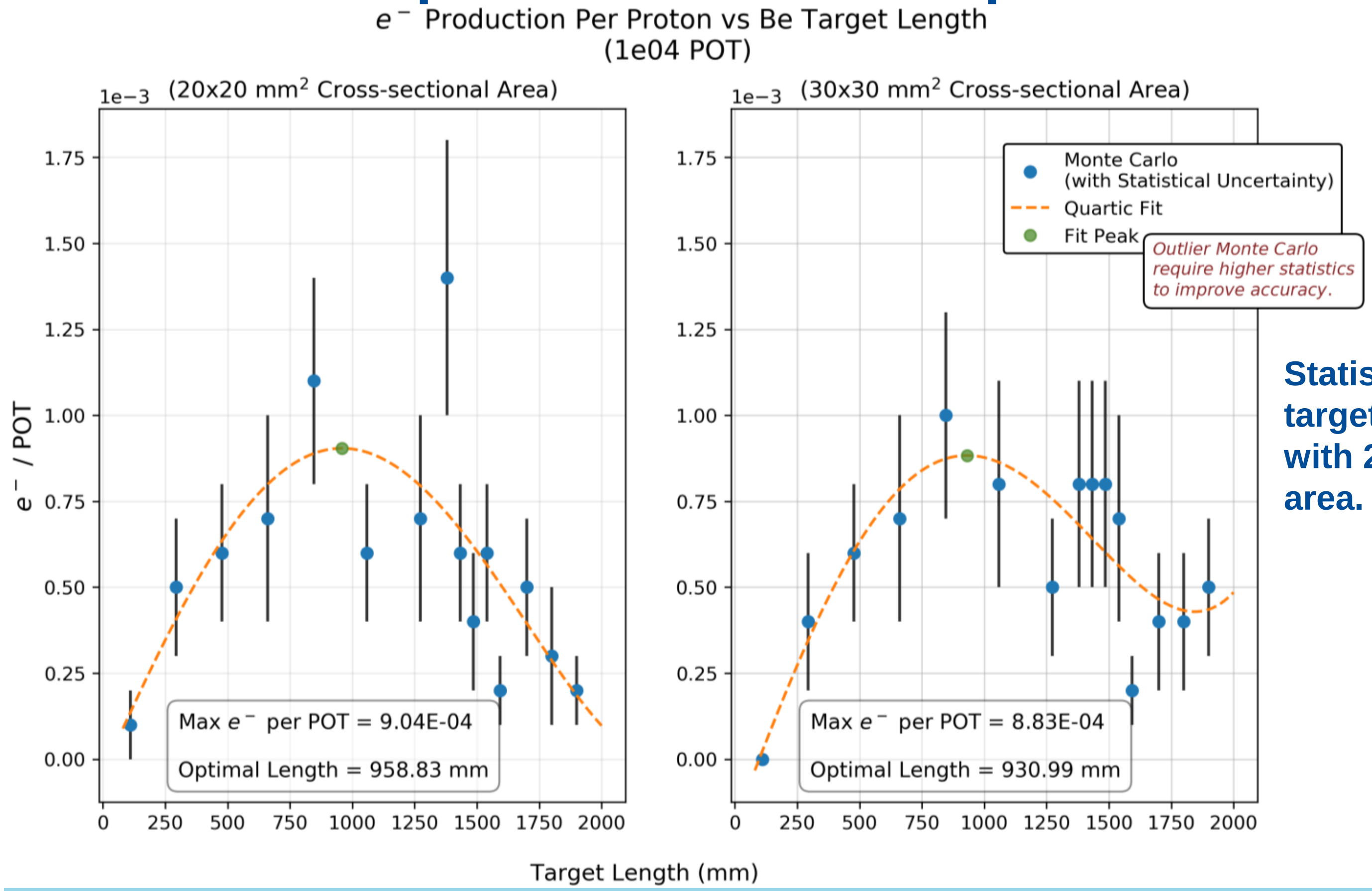




Higher statistics verify that higher energy secondaries are found at smaller bearings.

Ultra high energy electrons and positrons found within smaller angular distributions than charged pions of the same momentum bite.

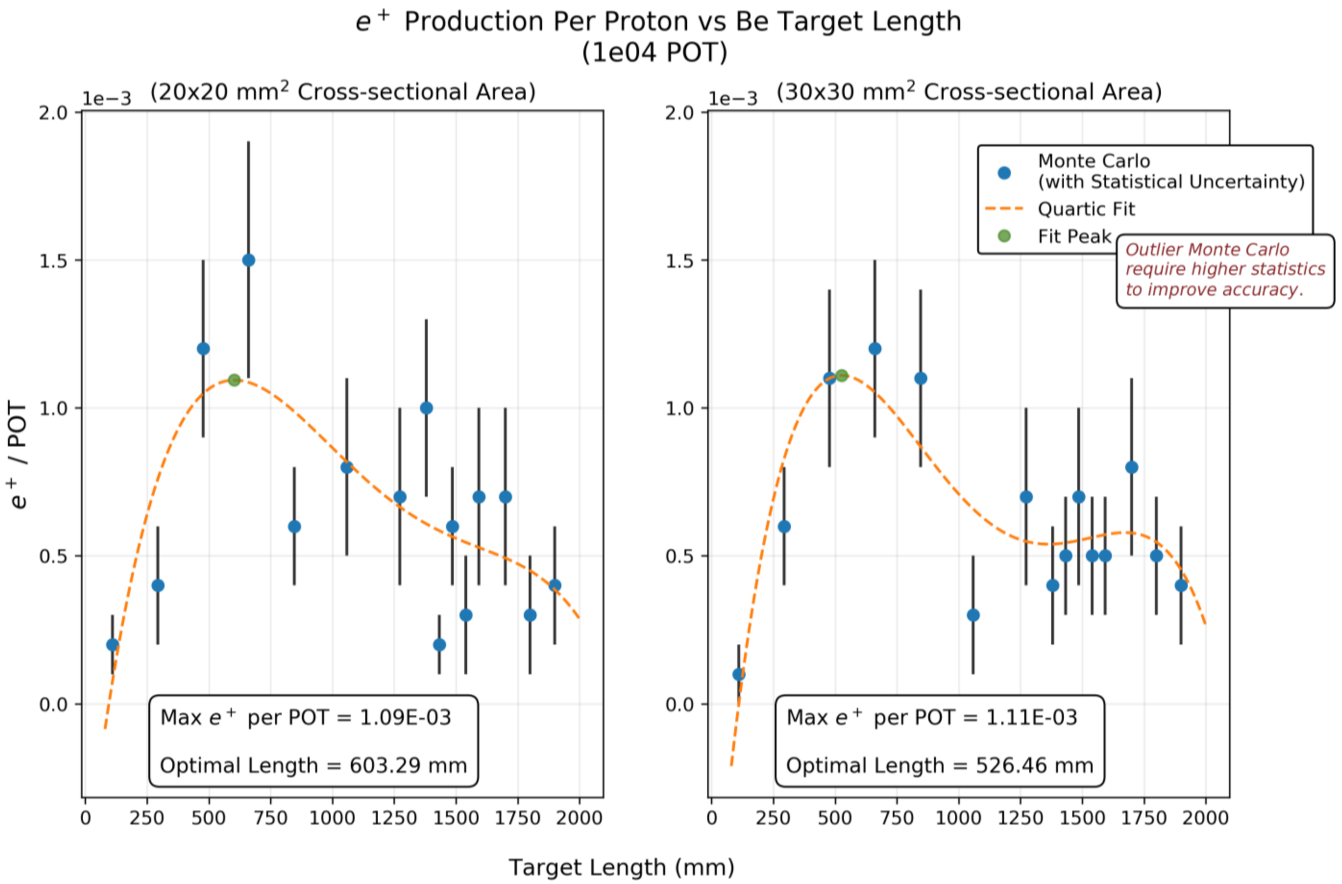
Dimensional Optimization for Prompt $e^{\pm}$ Production



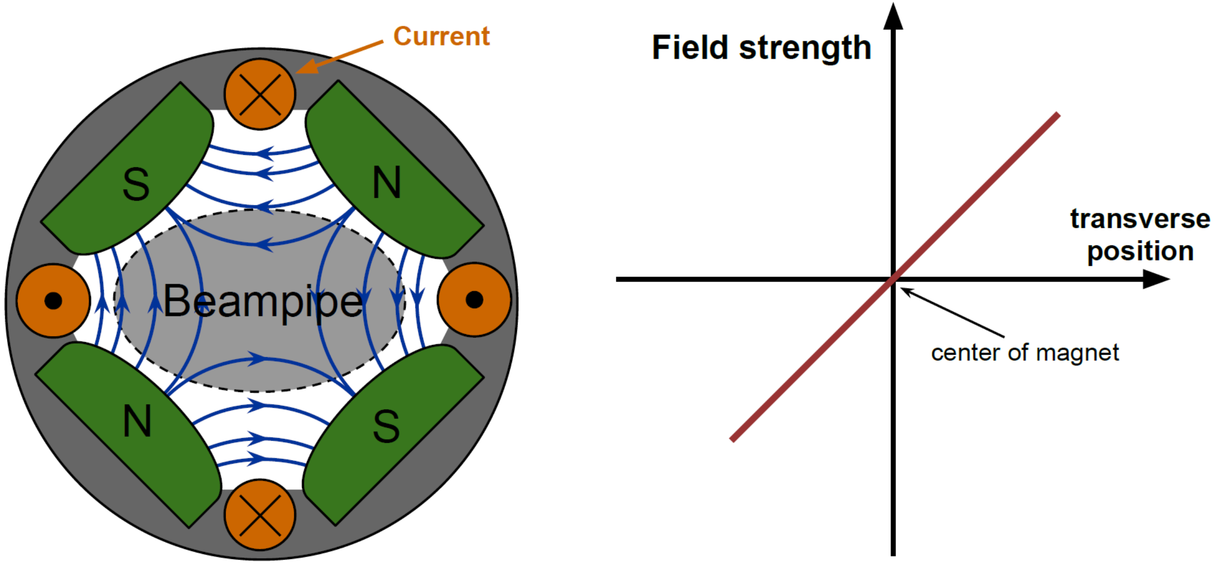
Statistics from 1e4 protons on target revealed better e^- production with 20x20 mm² cross-sectional area.

Fermilab

(continued for e^+)

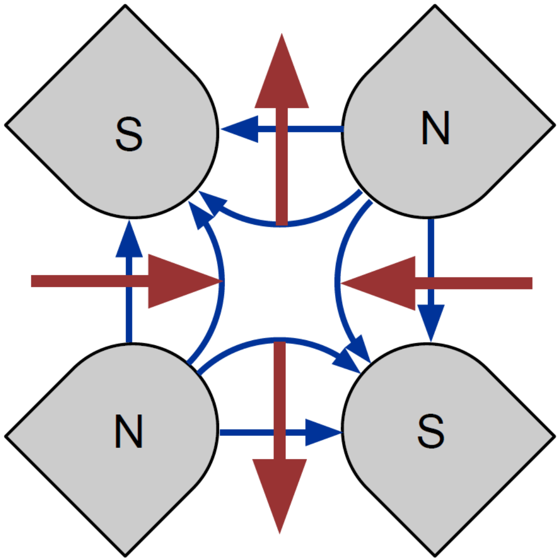


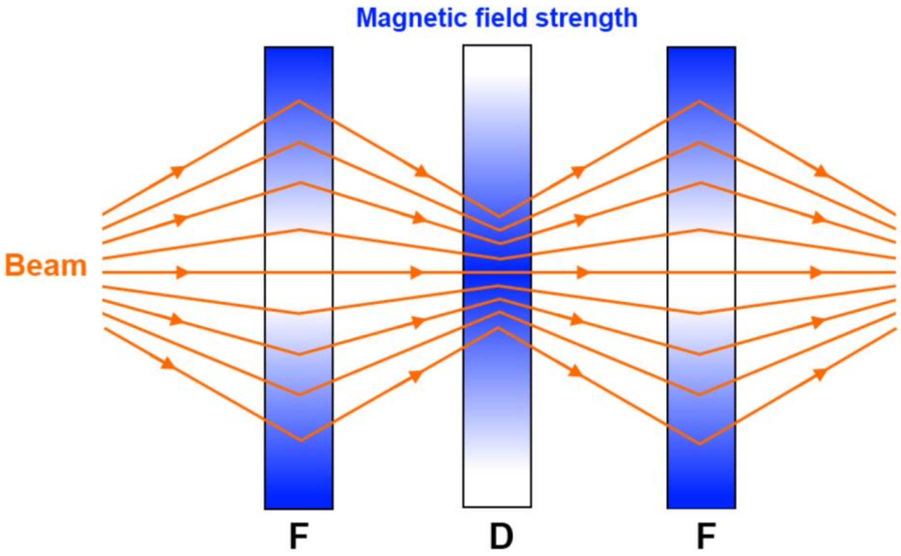
Strong Focusing Basics – Part 1 : Quadrupole Field Strength



Charged particles displaced transversely from the center of the magnet interact with the magnet's field. Field strength increases linearly so the further off the desired path the more the particle is focused in one plane and defocused in the other [6].

Quadrupole Focusing Basics – Part 2 : The Alternating Gradient

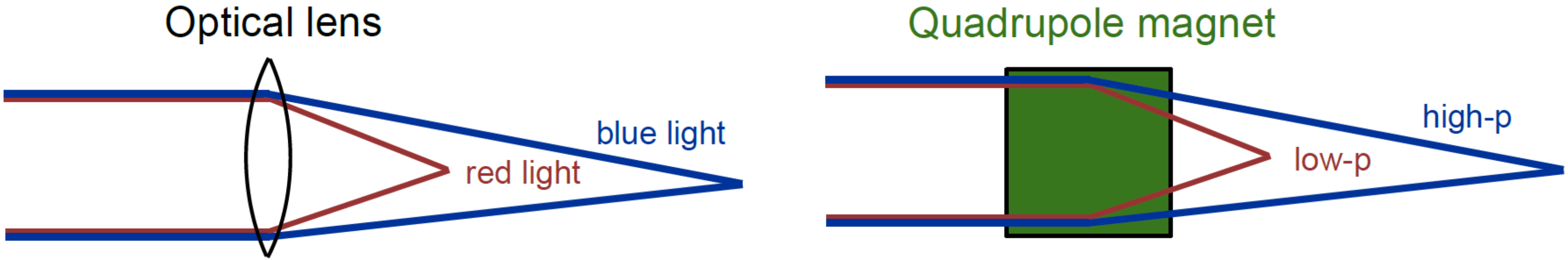




The blue lines show the direction of the magnetic field while the red show how the beam will be focused at the given polarity. This particular magnet would be classified as a focusing, or *F* Quad, as it focuses in the horizontal plane and defocuses in the vertical [6].

The blue and white color gradient is analogous to the magnetic field gradient. Defocusing quads have a negative gradient while focusing quads have a positive gradient. *Alternating Gradient Focusing* is displayed. A single unit for focusing is often referred to as a FODO cell. Multiple cells comprise a FODO lattice [6].

Quadrupole Focusing Basics – Part 3 : Focal Length



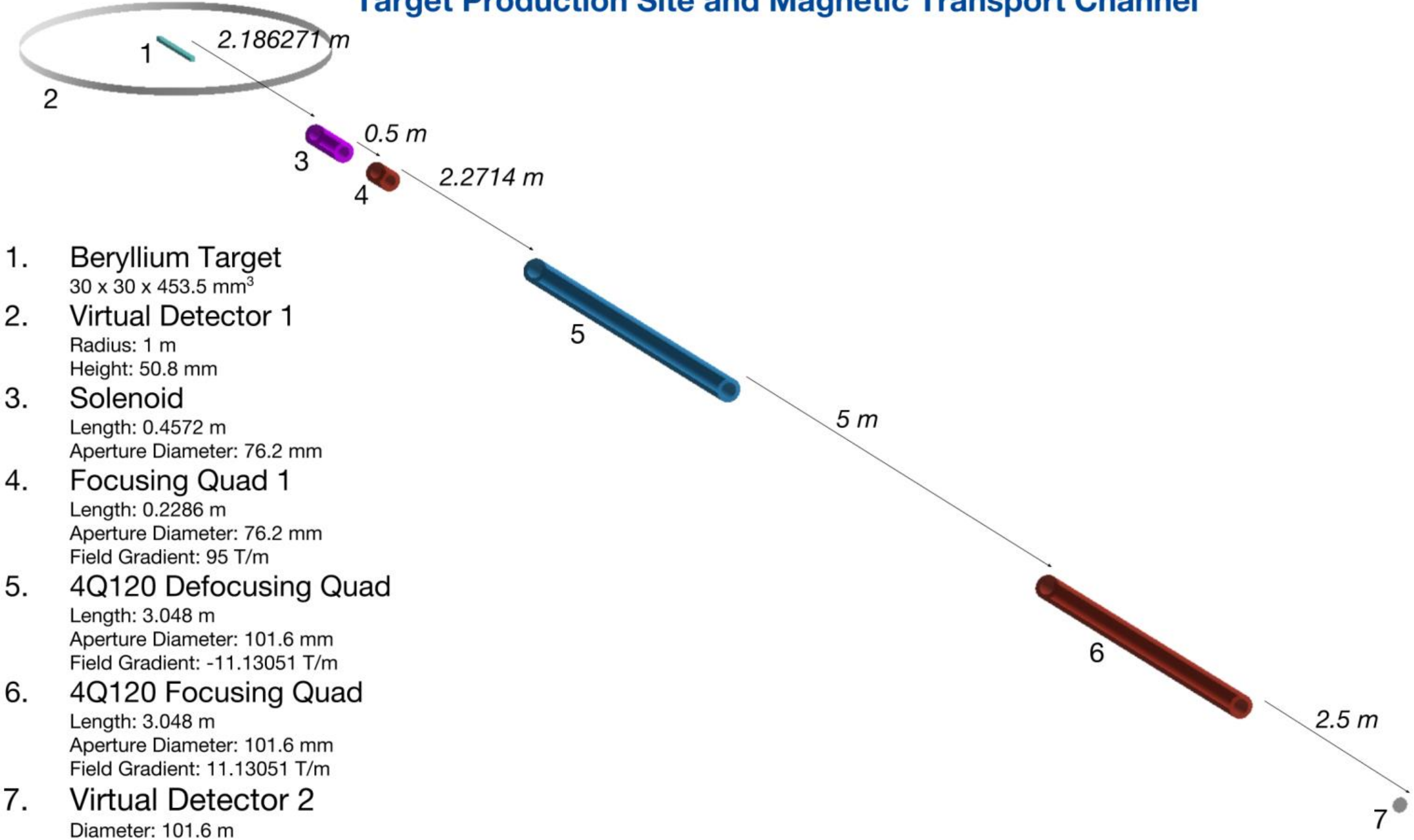
Similar to the longer focal lengths for higher frequency light, higher momentum particles focus further outward than low momentum particles [6].

Momentum Acceptance Verification

To confirm the minimum intensity of 5000 $e^{\pm}$ per spill at the experiment, optics for transport were designed.

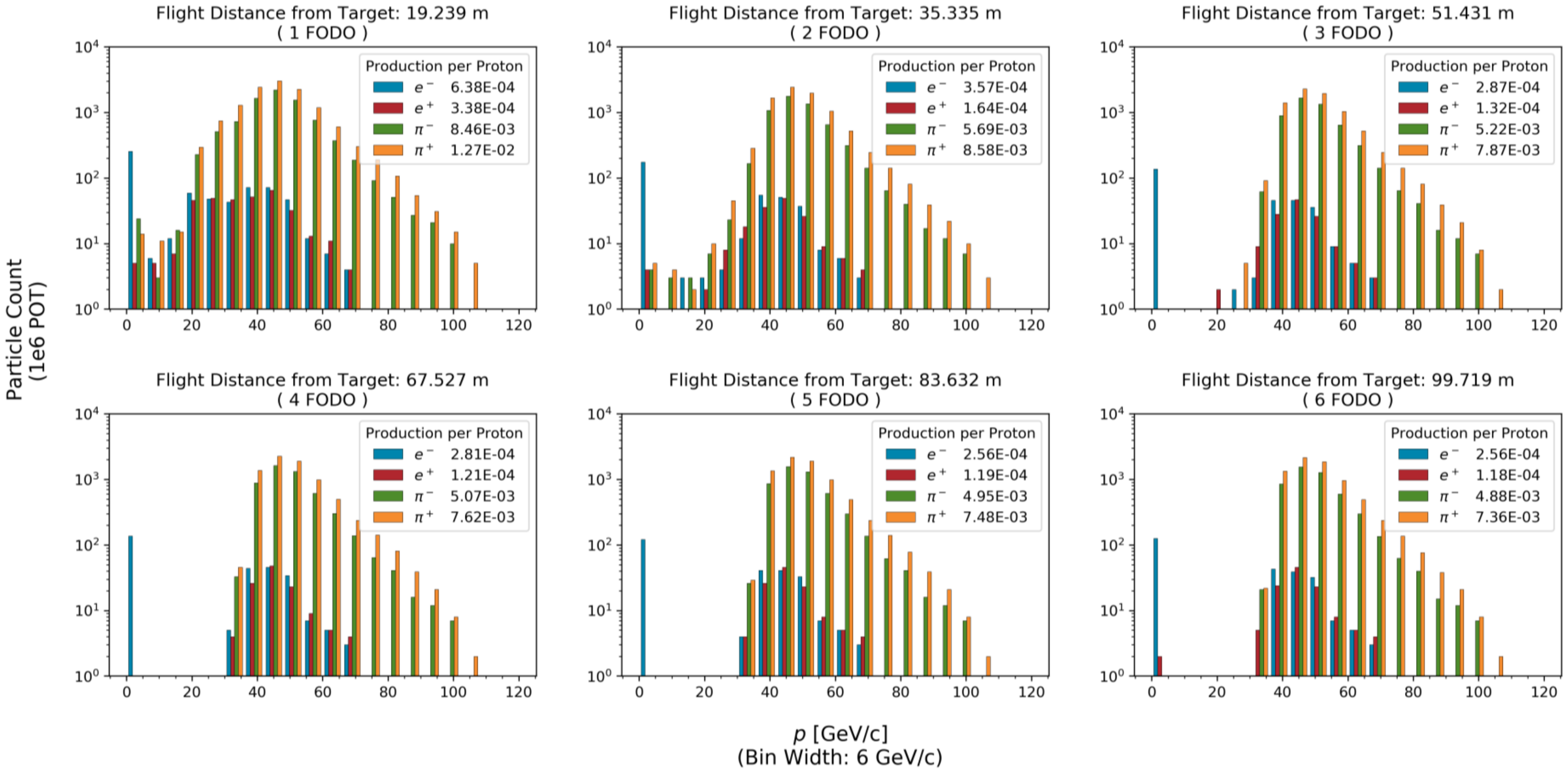
- Though separation optics are not complete, study of bulk intensities delivered would better approximate what users could expect at different energies.
  - A high loss estimate of 1 order for each intensity is assumed in calculations.
  - Significant losses occur during beam separation.
  - Magnetic transport channels must be tuned to specific momenta.
    - 50 GeV/c momentum bite with a wide acceptance of about $\pm$20% was designed for FODO cell tuning.
    - Placeholder optics were implemented to collimate the beam before injection into the lattice.

Target Production Site and Magnetic Transport Channel

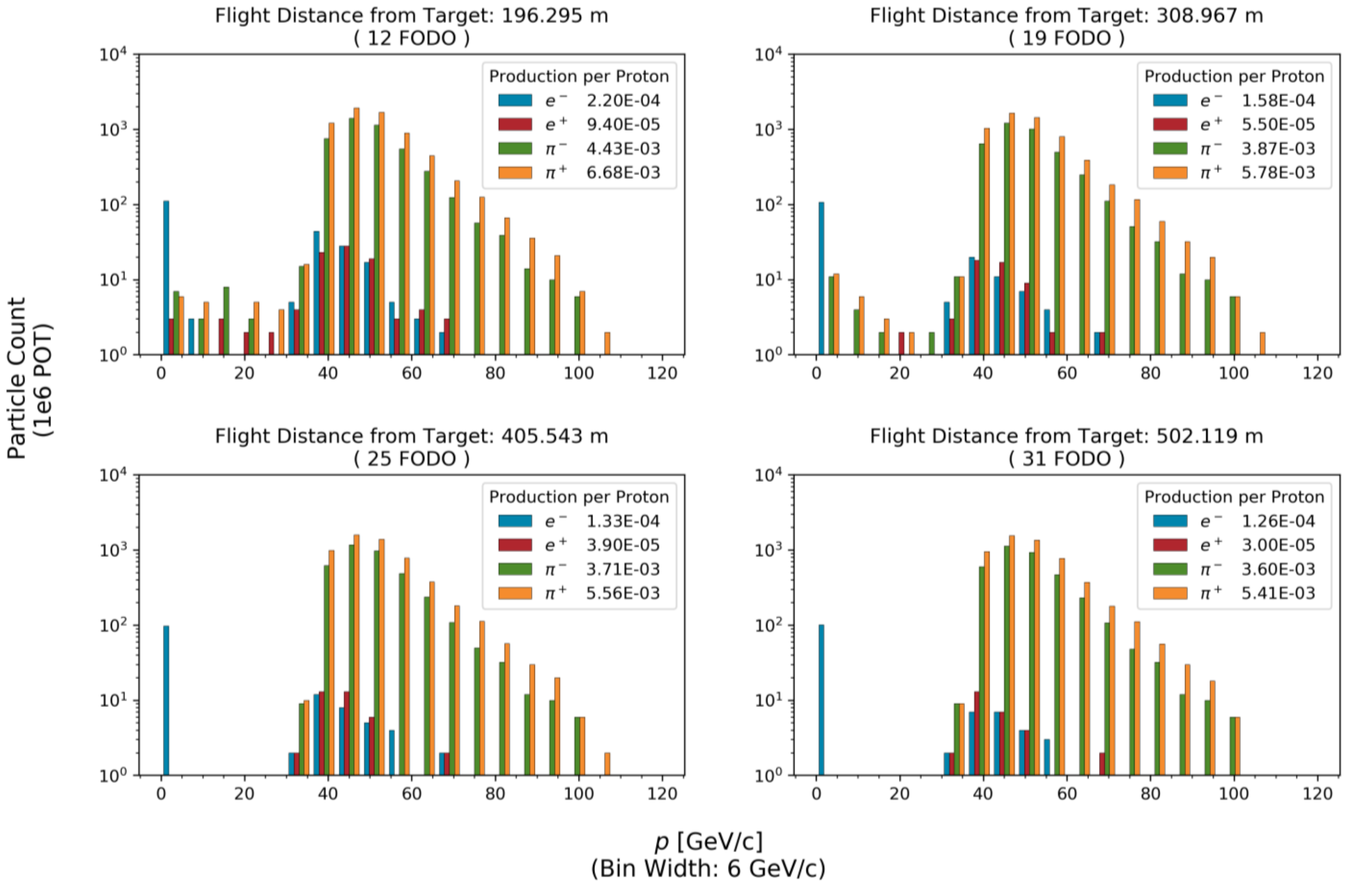


1. Beryllium Target
   30 x 30 x 453.5 mm³
2. Virtual Detector 1
   Radius: 1 m
   Height: 50.8 mm
3. Solenoid
   Length: 0.4572 m
   Aperture Diameter: 76.2 mm
4. Focusing Quad 1
   Length: 0.2286 m
   Aperture Diameter: 76.2 mm
   Field Gradient: 95 T/m
5. 4Q120 Defocusing Quad
   Length: 3.048 m
   Aperture Diameter: 101.6 mm
   Field Gradient: -11.13051 T/m
6. 4Q120 Focusing Quad
   Length: 3.048 m
   Aperture Diameter: 101.6 mm
   Field Gradient: 11.13051 T/m
7. Virtual Detector 2
   Diameter: 101.6 m

Intensity of p Distribution with Magnetic Transport - 1st 100 meters

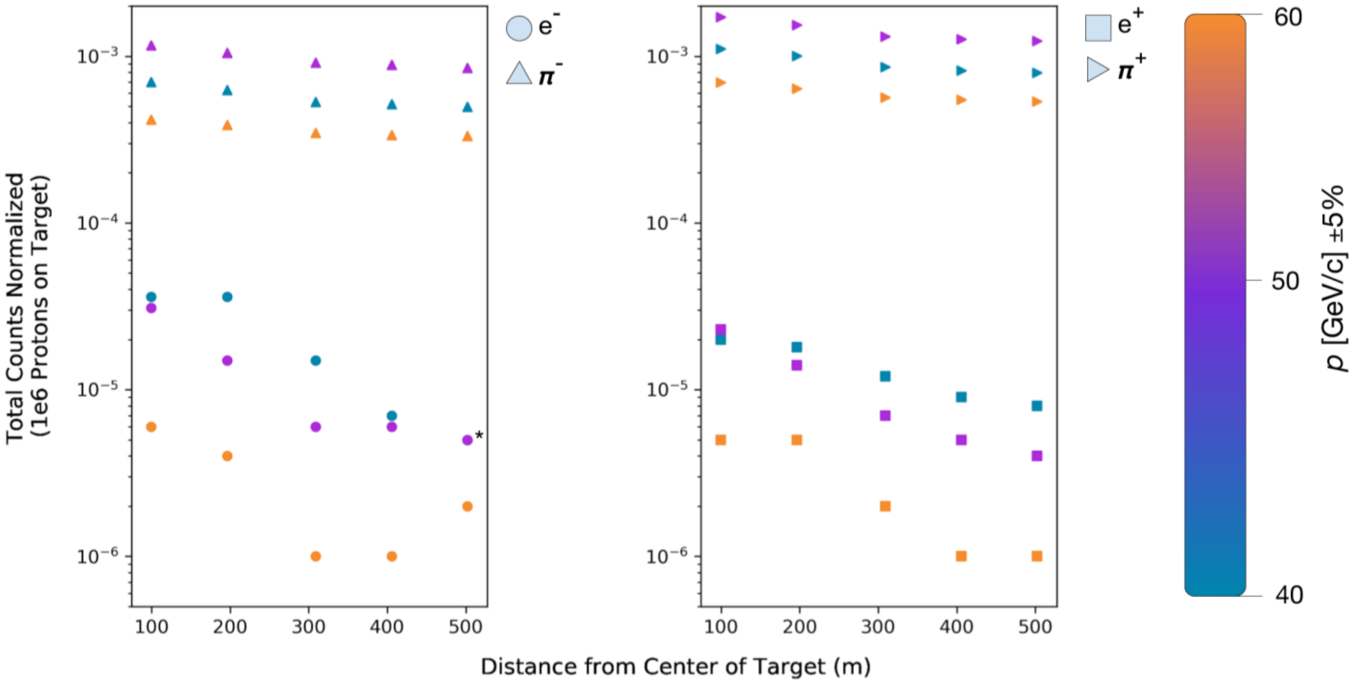


Intensity of *p* Distribution with Magnetic Transport (continued)



- 50 GeV/c *p* bite with ~20% acceptance verified

Particle Beam Partial Composition Evolution



Normed Momentum Bite Counts at 500 m

	e^-	e^+
40 GeV/c :	5e-6	6e-6
50 GeV/c :	5e-6	4e-6
60 GeV/c :	2e-6	1e-6

Strong focusing is tuned for 50 GeV/c.
10 ft quad length allows for large acceptance of ±20%

**Marker for 40 GeV/c e^- at 500 m is not visible as the 50 GeV/c e^- marker is on top.*

Electron and Positron Intensity Delivered to Experiment

Expected Momentum Bite Intensity with 1 Order of Loss				
p Bite [GeV/c] ±5%	MT4 Proton Intensity: 2e11		MT1 Proton Intensity: 1e13	
	e^-	e^+	e^-	e^+
40	1e5	1.2e5	5e6	6e6
50	1e5	8e4	5e6	4e6
60	4e4	2e4	2e6	1e6

Minimum requested spill intensity for e^- and e^+ is exceeded by 1 to 2 orders in MT4 and by 3 orders in MT1.
Minimum requested energy is exceeded by ~33% at 40 GeV/c bite to ~100% at 60 GeV/c bite.

Further study is likely to yield significantly higher returns.

References

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